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ASSOCIATION NOTES

THE INDUSTRIAL USE OF FLASH WELDING DEALING IN PARTICULAR WITH FERROUS MATERIALS

This report is intended to serve as a guide for industrial users of the flash welding process and sets out a field of application primarily as applied to mild steel. The types of joint which can be welded are outlined and details are given of the types of welding machine available, together with their particular features. The metallurgical background of the process, so far as it affects steels, is included. It is realised that the report does not answer all the questions that arise in production flash welding, therefore the Committee responsible for its preparation would be glad of any comments in order to obtain a clearer picture of the extent to which the report fails to meet the problems of the industrial user.

The four particular questions that the Committee would like to ask users of flash welding are—

(1) Are you satisfied that your flash welding machines are consistently turning out good welds?

(2) Would you make more use of flash welding if better quality could be guaranteed?

(3) Would you be interested in means of measuring or recording the electrical and mechanical performances

of your machine during operation to ensure consistency?

(4) Have you any special problems with reference to flash welding?

Answers to these questions would be more than appreciated.

This report was prepared by the FR.4 Committee of the B.W.R.A. on the Flash Welding of Steels. Members of the FR.4 Committee are as follows:—

Dr. J. S. Blair (*Chairman*)	Stewarts and Lloyds Ltd.
H. Brooks	Ministry of Supply
G. Burns	Admiralty
Dr. M. S. Fisher ..	Royal School of Mines
E. W. Harding ..	Ministry of Supply
H. W. G. Hignett ..	Mond Nickel Co. Ltd.
R. S. Pickering ..	Rubery Owen & Co. Ltd.
C. L. Railton ..	T.I. (Group Services) Ltd.
J. M. Sinclair ..	A.1. Electric Welding Machines Ltd.
N. A. Tucker ..	Johnson, Matthey & Co. Ltd.

Technical Secretary: J. H. Gameson

THE EFFECT OF STRAIN-HARDENING ON THE EQUALISATION OF MOMENTS IN THE SIMPLE PLASTIC THEORY

In a report entitled "Extension of the Simple Plastic Theory to take Account of the Strain-Hardening Range," by J. W. Roderick and J. Heyman (B.W.R.A. Report, Reference FE.1/15), tests on simply supported beams of varying carbon content were described. Some of the information obtained has been used for a theoretical investigation of the assumption in the simple plastic theory regarding the extent to which equalisation of bending moments in a redundant beam on portal tends to occur after yielding has taken place. This investigation is outlined in Report R.67, "The Effect of Strain-Hardening on the Equalisation of Moments in the Simple Plastic Theory," on pages 147*r* to 153*r* of this issue.

It is shown that for steels with a small plastic range, attention must be given to the effect of strain-hardening if an ultimate design method is to be developed. For mild steel beams and portal frames, the simple plastic theory provides a satisfactory basis for design and gives a close estimate of the bending moment distribution at collapse.

This report was prepared for the FE.1 Committee of the B.W.R.A. on Load Carrying Capacity of Frame Structures, the Members of this Committee are as follows:—

Professor J. F. Baker (*Chairman*)	University of Cambridge
J. Anderson	Imperial Chemical Industries Ltd.
H. A. Cadwell ..	Edward Wood & Co. Ltd.
Everall, W. T. ..	
P. C. G. Hausser ..	R. T. James and Partners
H. V. Hill	Ministry of Works
C. Hipwell	Redpath Brown & Co. Ltd.
W. A. Mitchell ..	Husband & Co. Ltd.
F. A. Partridge ..	Braithwaite & Co. (Engineers) Ltd.
Professor A. G. Pugsley	University of Bristol
G. Roberts	Freeman, Fox and Partners
Dr. J. W. Roderick ..	University of Cambridge
F. J. Samuely ..	
Dr. F. G. Thomas ..	D.S.I.R. (Building Research Station)
S. Vaughan	Oscar Faber & Partners

Technical Secretary: R. P. Newman

B.W.R.A. SUMMER SCHOOL

The Association is to hold a summer school on "Welding Design and Engineering" at Ashorne Hill, near Leamington Spa, from Saturday, 6th May, to Saturday, 2nd June, 1951, inclusive. The school is primarily intended for welding engineers, designers and inspectors who have at least an elementary knowledge of welding applications.

The morning sessions will consist of general subjects; afternoon sessions—specialised lectures on pressure vessels, structures, shipbuilding and general machinery constructions. In the evening, discussions will be held on such subjects as Deformation in Welding, What Hinders the Wider Application of Welding? etc. Lectures will be given by experts on the various subjects including Members of the B.W.R.A. staff. Other details will be published shortly; fuller details may be obtained on request from the Secretary, British Welding Research Association, 29, Park Crescent, London, W.1.

STEEL ECONOMY

A Summary of the Fourth Report of the Steel Economy Committee has just been issued, and it is interesting to find on page 8 of this document the following:—

"Of all the aspects of steel economy which the Committee has discussed with the various interested bodies, none has been more vigorously pursued than the promotion of welding by the Institute of Welding and the British Welding Research Association. These two bodies organised a Symposium on Steel Economy by Welding at which a most comprehensive series of papers were read and discussed, much on the lines recommended in the Committee's Third Report. The papers read covered a very wide field of steel utilisation; they have been widely circulated, and it is hoped that they will be closely studied by designing engineers who can acquaint themselves with the advances which are being made, not only in their own particular industries, but in others where the basic problems are much the same."

The papers referred to were published in *Transactions of the Institute of Welding* and *Welding Research* Supplement and copies, either in the form of back numbers of the *Transactions* or *Welding Research*, or as reprints, may be obtained from either the Institute of Welding or the British Welding Research Association.

ERRATA

Page 134r. - B.W.R.A. Summer School.

For "6th May" please read "26th May"

R.66

The Industrial Use of Flash Welding, Dealing in Particular with Ferrous Materials.

This Report was first issued to Members of the British Welding Research Association as a Confidential Document in November, 1950

A. INTRODUCTION

Flash welding is a mechanised welding process used mainly for making butt joints in steel. This memorandum is intended to serve as a guide for industrial users of the process, in connection with the welding of ferrous materials. The process can also be applied to some non-ferrous metals, including aluminium alloys, and the memorandum may be helpful to those interested in such applications, since the principles involved are the same, but it must be pointed out that machines designed for flash welding steel are not generally suitable for welding non-ferrous alloys.

Historically, flash welding machines are a direct development from the earliest type of resistance welder, the original simple butt welder devised by Elihu Thomson in 1866. This was an apparatus "consisting essentially of two copper clamps insulated from each other and capable of being moved towards or away from each other by means of a powerful screw or lever." The components to be welded were held in the clamps, their ends brought into contact under pressure and a low voltage current from the secondary of a transformer passed through the circuit so formed. The work-pieces between the clamps became heated as a result of their resistance to the passage of the current, the highest temperature being attained at the contacting faces, as a result of the maximum resistance being at this position. When the contacting faces reached a sufficiently high temperature to weld together, the longitudinal pressure completed the weld by forging it and the current was cut off.

In the simple resistance butt welder, which is still largely used for welding wire and light gauge rods into continuous lengths, the whole region between the clamps attains a high temperature by the time the abutting faces reach welding heat and, during the forging action, all this region undergoes appreciable upsetting. Any oxide that has formed may not be adequately removed and in the case of light sections having little rigidity buckling may occur.

These and other disadvantages placed limitations on the wider application of the process which were only overcome with the introduction of the "flashing" action which gave to the modified process the name of "Flash Butt Welding," now commonly abbreviated to "Flash Welding."

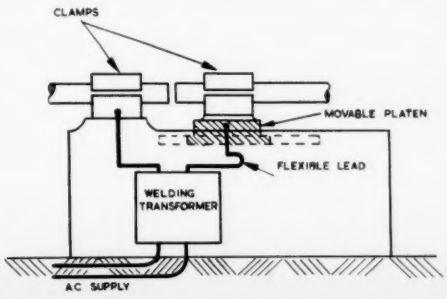


Fig. 1. Diagrammatic arrangement of flash welding machine.

In the flash welding process the machine remains in its essentials the same but the procedure is different. Instead of the current flow being initiated after the work-pieces have been pressed firmly together, as in the simple resistance welding process, in the flash welding process the transformer is switched on while the workpieces are still separated and then they are brought together under light pressure; electrical contact is thus established at a few isolated points rather than over the whole of the abutting faces. The high current flowing through these small contacting areas rapidly melts and partially vaporises the metal there, flashing it away in an explosive manner. The abutting surfaces are moved towards each other to establish contact at further points which, in their turn, are melted and flashed away. This process continues with much sparking and flashing, generating intense heat at the contacting surfaces and gradually burning them away as the components are moved slowly towards each other. At the same time heat is being conducted back along the work-piece establishing a plastic zone behind each of the flashing faces. When satisfactory temperature conditions in the work-pieces are reached the movement of the faces towards one another is accelerated rapidly, pressing them forcibly together. The current is switched off and the weld is forged and consolidated extruding the overheated metal from the flashing faces to form a fin round the joint.

The chief advantages of the process compared with resistance butt welding are the localisation of heating, low power consumption and the rapid action which lends itself to fully automatic operation.

B. FIELDS OF APPLICATION

(a) Material

Provided the components are designed to suit the fundamentals of the process, the field of application of flash welding is almost unlimited. Properly made welds in mild steel are as strong and ductile as the unwelded material and require no heat treatment after welding. Welds in higher carbon steels and alloy steels generally need some form of heat treatment if the properties of the joint are required to equal or approach that of the parent metal. For some types of steel, including medium carbon steel in the normalised condition and medium alloy steels hardened and tempered to a moderate tensile strength, a simple tempering treatment is all that is necessary. For others, including high tensile alloy steels and austenitic stainless steels susceptible to weld decay, full heat treatment is required after welding. Cold worked steels are softened locally by flash welding, but the loss of strength may be unimportant and the original strength can sometimes be restored by heat treatment. Further information regarding materials and heat treatment is given in section G.

(b) Form of Components

The following are typical examples of flash welding applications:—

(i) *Joints in Straight Symmetrical Sections.*—Bar to bar joints, Figs. 2 and 3. Familiar applications are machine

EXAMPLES OF FLASH WELDED JOINTS

STRAIGHT SYMMETRICAL SECTION

Fig. 2

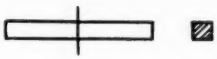


Fig. 3

Fig. 4

SYMMETRICAL SECTION AT JOINT ONLY

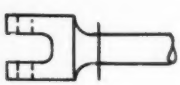


Fig. 5

Fig. 6

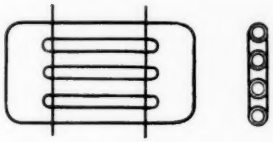


Fig- 7

SIMPLE FLAT SECTION

Fig. 8

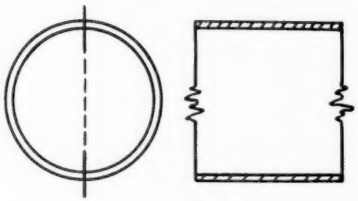


Fig. 9

COMPLEX FORMS

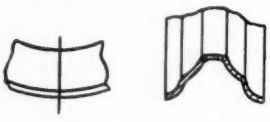


Fig. 10

Fig. 11

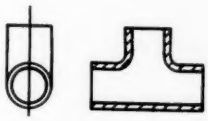


Fig. 12

LIGHT ROLLED STEEL SECTION

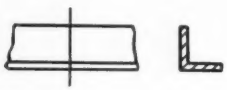


Fig. 13

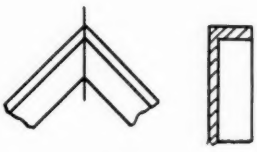


Fig. 14

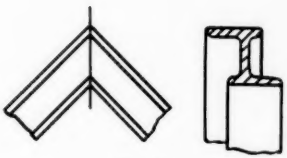


Fig. 15

HEAVY SECTION

Fig. 16

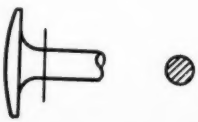


Fig. 17

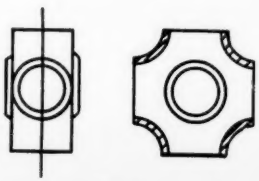


Fig. 18

tools and drills where tool steel is required to be attached to a lower carbon steel shank.

Tube to tube joints, Fig. 4. Joints of this type are used for joining boiler tubes and the war-time petrol supply lines across the Channel.

(ii) *Joints having a Symmetrical Section at the Joint only.*—Track or connecting rod end, Fig. 5. Axle casing, Fig. 6. Radiator parts, Fig. 7.

(iii) *Joints in Simple Sections.*—Strip to strip, Fig. 8. This type of joint may vary in width from a fraction of an inch to several feet. It is often used for joining coils of strip or lengths of sheet into continuous lengths for further rolling or for forming into tubes.

Longitudinal joints in cylinders or drums, Fig. 8.

(iv) *Complex Forms.*—Cycle and motor car wheel rims, Figs. 10 and 11. Tubular fittings, such as Tees, Fig. 12.

To the examples illustrated can be added the flash welding of motor car bodies where the two side panels are flash welded to the centre section. Such a joint may be several feet in length and, if desired, the two joints can be welded simultaneously.

(v) *Joints in Light Rolled Steel Sections.*—Straight and mitre joints in rolled steel angles, Figs. 13 and 14.

Mitre joints for window frames, Fig. 15.

(vi) *Joints in Heavy Sections.*—Track rails, Fig. 16. Buffer ends, Fig. 17. Propeller bosses, Fig. 18.

C. WELDING MACHINES

(a) Types of Machines

The essential parts of a flash welding machine are clamps for holding the work-pieces, a means of moving them towards one another, dies for leading current into the work-pieces and a suitable source of current.

Usually the two clamps, comprising an upper and lower jaw each, are mounted on platens on a robust bed plate, one of the platens and its associated clamp being fixed while the other is movable in an axial direction.

The dies for leading in the current may be separate units or the functions of the dies may be performed by the clamps. Sometimes, when the clamps serve as dies the current is only led into the bottom half; this is, for many purposes, adequate, but there are instances, such as welding of tubes, in which this arrangement is not satisfactory because of non-uniform current distribution.

Flash welding machines may be divided broadly into two classes depending on whether the principal mechanical operations, movement of the platen and application of the upsetting pressure, are performed manually or are power operated. Power operated machines can be rendered automatic to a large degree and are to be preferred for large scale repetition work where consistent reproduction of all factors influencing the quality of the weld is of prime importance.

(i) *Manually Operated Machines.*—The clamps are usually hand closed by means of a toggle or cam arrangement. Current flow is initiated by a push button or foot switch and is terminated by a cut-out switch which may be operated directly by hand or indirectly by the movement of the platen. Platen movement is by means of a lever or hand wheel operating through a cam or other suitable mechanism, and the speed of movement and magnitude of the upset pressure are dependent on the judgment and strength of the operator; in consequence this type of machine cannot be expected to give the highest grade of consistency and, in any case, is only applicable to the lighter sections where the upset force required does not exceed 1 ton.

Where the size of the section is too great to permit flashing from cold, preheating can often be successfully employed. This is done by bringing the components firmly together and after a few seconds parting them, with the power swiched on. This is repeated until the faces are hot enough to allow continuous flashing to proceed.

(ii) *Power Operated Machines.*—The principal feature of this type of machine is that the movement of the platen and application of the upsetting pressure are power operated using either hydraulic or pneumatic pressure or a mechanical drive. Clamping is usually power operated to achieve the high clamping pressures necessary for sections requiring substantial upsetting forces. It is convenient, and almost invariably the practice, on these machines to arrange that all operations from the initiation of flashing to the final upsetting and current cut off shall be automatic and controlled to a predetermined programme which is repeated precisely for every weld.

When, as is frequently the case, pre-heating is necessary it may be arranged on this type of machine in one of two ways.

(b) Methods of Pre-heating

(i) *Manual Pre-heating.*—During the pre-heat stage the machine is under manual control of the operator and the operation is carried through in accordance with his judgment (as mentioned in Section C (*a*) (i)). At the conclusion of this stage, when continuous flashing can be maintained, control of the remaining stages is turned over to the automatic control.

(ii) *Automatic Pre-heating.*—In this type of machine the pre-heating operation is under automatic control. If the change over from pre-heating to flashing also takes place automatically, this is known as fully automatic pre-heating. Further details of pre-heating are given under Section E (*e*).

(c) Welding Current

This is generally obtained from a transformer with a primary winding tapped to provide a series of steps of adjustment to cope with a reasonable range of sizes of work-piece. Where a specially wide range of work must be welded on one machine an auto-transformer can be used to provide a greater range of adjustment than is practicable with the tapped primary of the welding transformer.

Open circuit secondary voltages employed for flash welding usually lie in the range of 2 to 20 volts, though not all of this range would be available on any one machine. The range available depends on the size of the machine and on the design of the secondary loop. The flashing voltage will be lower than the open circuit voltage as a result of the resistance and layout of the leads and windings forming the complete secondary circuit.

The actual secondary welding current depends on so many factors that it is not possible to give values which would be useful as a guide to setting up the machine. Furthermore, there are at present no reliable methods of measuring the secondary current, though the primary current read from a well-damped ammeter or recorder when multiplied by the turns ratio of the transformer will give an approximate indication.

In addition the secondary current required depends on the time of flashing. Consequently, if the recommended flashing time, amount burned off and other factors are adhered to (*see* (E) Welding Variables), the secondary current will largely look after itself, though the graphic ammeter record is useful to ensure future consistency or for comparison of different work-pieces on any one machine.

For a given flashing time, insufficient current, *i.e.* too low a voltage tap, will cause too cold a weld or an actual "freeze up." Too much current will cause burning or melting.

(d) Electrical Power Supply

Transformers in flash welding machines are inherently single phase and normally connected across two phases of the three-phase supply. Consideration should be given to the electrical supply available, due to the single phase load, but there are methods for minimising its disturbing effect; these are described in the Appendix.

(e) Dies

The main function of the dies is to lead the welding current into the work-piece, and they must have good electrical conductivity and must so fit the work-piece as to give an ample area of contact to avoid heating effects in the dies caused by excessive current density.

The current flowing from the fixed die to the movable die through the work-piece takes the path of least resistance and, since the resistance of the work-piece is almost always greater than that of the dies, the current pick up to the work-piece is concentrated at the ends of the dies nearest the weld position. Further, this part of the die is most subject to heat being conducted back along the work-piece from the flashing faces and to spattering with hot metal thrown out during flashing. To reduce these high temperatures, dies are normally water cooled, but it is still necessary for the die material to be resistant to abrasion and retain its hardness at elevated temperature.

Die materials are almost invariably copper-base alloys, and the best and most economical selection among these alloys for a particular job will depend on

1. Quantity and rate of production.
2. Current density in the dies.
3. Clamping pressure.
4. Surface condition of the work-piece.

The first factor is self-evident in that a large number of welds at a high rate of production would justify the use of more expensive die materials. As a rule ordinary unalloyed copper is satisfactory when only a small number of welds have to be made.

The second factor is, of course, related to the ratio of the surface area in contact with the die to the cross section of the work being welded.

The third and fourth factors relate principally to cases in which the dies are used as clamps. In these circumstances higher hardness to withstand the clamping pressure and abrasion by the work-piece is required than if the dies are only conducting current and need only sufficient pressure to establish good electrical contact, while taking no thrust.

Copper-cadmium and copper-chromium alloys of the types generally used for spot-welding electrodes are often employed as die materials in flash welding machines, but on account of their relatively low softening temperatures, mechanical and electrical erosion of the edges of the dies tends to be rapid. For most high speed production applications a good type of clamping die consists of a high duty copper alloy faced at the critical points (or loading edges) with a hard material of reasonable conductivity, such as one of the proprietary copper tungsten materials. These materials have softening temperatures which may be as high as 1000 deg. C. and hardnesses of over 250 D.P.H.

An operational point in connection with dies is that surfaces which contact the work must be kept clean and in good condition and should not be allowed to become contaminated with embedded particles of spatter from the flashing operation. Poor electrical contact in the dies resulting from badly maintained surfaces will give rise to adverse heating effects and may also cause copper to be picked up on the work-pieces.

(f) Clamps

The function of the clamps is to hold the pieces in good alignment, and they should be of ample size to enable adequate axial pressure to be applied to the work-pieces, without slipping and without having to make the clamping pressure per unit area of contact so high as to damage or distort the work-pieces.

The contact surfaces of the clamps must be reasonably hard to resist the abrasive action involved in applying axial thrust to the work-pieces, without wearing to such an extent that alignment becomes unsatisfactory.

On occasions when, as a result of design features of the component being welded, it is not practicable to make the clamps large enough to apply an adequate clamping force without damage to the work-piece, the clamps must be supplemented by some form of rigid support, bearing against the free ends of the pieces; this is usually referred to as end-stopping or backing-up. End-stopping may be necessary for other reasons than the above, or may occur automatically from the shape of the work-pieces.

For end-stopped work clamping forces may be of the order of 3,000 to 4,500 lbs., for each square inch of the area to be welded.

For work which is not end-stopped the minimum clamping force necessary is usually taken to be about one-and-a-half times the upsetting force. Thus, as can be seen later, where for mild steel the upsetting pressure may be up to 4 tons per square inch, the clamping force should not be less than 6 tons for each square inch of cross-sectional area to be welded. In the case of alloy steels where the upset pressure may reach 8 tons per square inch the clamping force should be not less than 12 tons for each square inch of the area to be welded.

The clamps (and dies if separate ones are used) may be operated by hand mechanisms or by pneumatic, hydraulic or mechanical means.

Pneumatic methods are generally regarded as the fastest in operation, but space considerations may limit their use. For heavy sections calling for high clamping forces, hydraulic or combined air-hydraulic operation is to be preferred though automatic mechanical operation is sometimes used. When the operating mechanism can conveniently be linked with the machine mechanism the operation of the clamps can be timed in conjunction with the other stages of the welding cycle.

Both pneumatic and hydraulic types should preferably be worked from an independent accumulator system and the direct force can be multiplied by levers provided that speed of operation is not diminished too much.

The clamping of thin walled tubes for welding calls for particular care to avoid crushing or distortion. Supporting the tube by internal mandrels is not usually practicable, and the only satisfactory solution is the use of the largest possible clamping surface coupled, if necessary, with end-stopping.

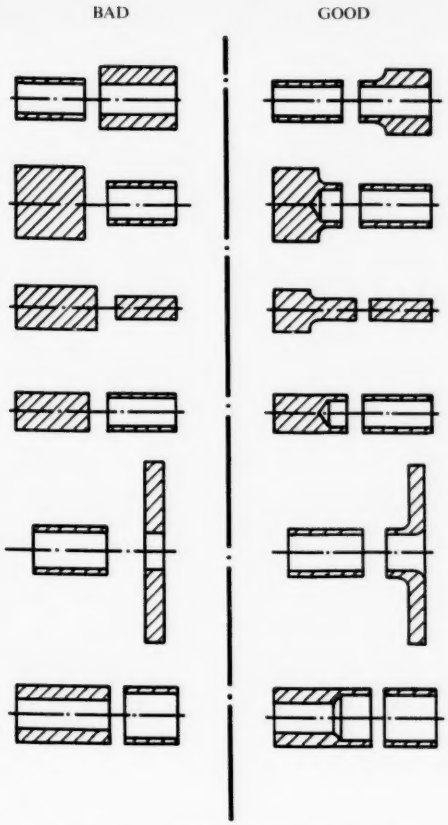


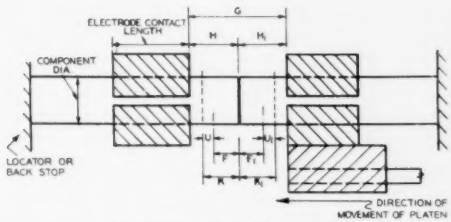
Fig. 19. Examples of good and bad joint designs.

provide a sufficient clamping area for the upsetting force to be applied without the pieces slipping in the clamps. However, it is generally desirable that the outer ends of the work-pieces should bear against fixed end stops on the platens so that the forging pressure may be transmitted to the work-pieces by the stops.

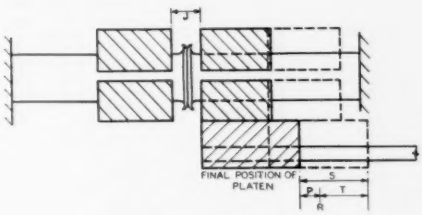
(b) Preparation of Work

In most assemblies little preparation of the abutting faces is required apart from ensuring that they are clean, not excessively ragged and are approximately parallel to each other. Bevelling or rounding of the faces may be used to facilitate flashing in cases where the sections are too heavy to flash directly from cold, but not so large as to call for full pre-heating.

On clean or machined components no special preparation is usually required except at the current clamps. Scale, rust, grease or oil should be removed from the weld faces and from the areas of the work pieces that are to contact the dies.



AT COMMENCEMENT OF FLASHING.



AT COMPLETION OF WELD.

MATERIAL ALLOWANCES

G—Initial distance between clamps.
H, H_1—Initial overhang of component.
J—Final distance between clamps.
K, K_1—Material lost for each side.
F, F_1—Material lost in flashing each side
U, U_1—Material lost in upset each side.

PLATEN MOVEMENT

S—Total stroke (equal to $K+K_1$).
T—Flashing stroke (equal to $F+F_1$)
P—Upset stroke (equal to $U+U_1$).
R—Release point for upsetting force.

Fig 20. Schematic illustration of material allowances and platen movement.

D. WELDING PROCEDURE

(a) Design of Joints

When designing a joint for flash welding, the following points should be borne in mind to achieve satisfactory welding conditions:—

1. The sections at the joint on both components should be approximately equal in area. Discrepancies of area of up to 15 per cent. may be tolerated, but it is preferable that the correspondence should be better than this. At no point between the weld face and the die should the cross-sectional area be less than at the weld face.

2. The section at the joint should be uniform on each component for a minimum distance equal to one-and-a-half times the amount of material to be lost from each component.

3. The design should permit of clamping over a sufficient length to ensure that satisfactory alignment is maintained during the upsetting action and, if possible, should

(c) Set Up

Accuracy in axial alignment and overall length after flash welding can be of a very high order. Mis-alignment, due to distortion by the welding heat, is practically nil.

The accuracy that can be obtained in production will be influenced by:

1. Tolerances in the parts before welding.
2. Rigidity and precision of the welding machine and fixtures.
3. Maintenance of the machine, particularly of the dies and clamps so as to limit wear and to compensate for its effects.
4. Care used in loading work into the machine to avoid damage or mis-alignment.

(d) Upset Travel

The length of a welded component is not usually required to be held within very close limits, so the normal procedure is to allow the upset movement to proceed until the resistance of the work-piece to deformation balances the upsetting force; this is described as "unlimited upset." These conditions afford a measure of compensation for variations of the temperature gradient established in the work-pieces before upsetting, since the upset continues until the overheated metal has been forced out and the zones that are at a satisfactory welding temperature have been reached. In this way, adequate forging of the weld is ensured, assuming that the upset speed and pressure are suitable. Further comments on temperature gradient and on upset speed and pressure are made in Section E.

Where the final length must be to close limits, it is necessary to place a definite restriction on the upset of the platen. This practice is described as "limited upset." It necessitates critical control of the welding variables.

As an illustration of the degree of dimensional accuracy that can be attained, it may be stated that in one application $\frac{3}{8}$ in. diameter valve stems are flash welded to valve heads with a production of tolerance of 0·004 in. total eccentricity at the weld, and a maximum variation in length of 0·005 in. To obtain these production tolerances, the parts are centreless ground to a high degree of accuracy before welding, special precision welding machines and fixtures designed for the purpose are used, and careful attention is given to die maintenance and loading of work.

Another instance in which limited upset may have to be used is when a machine is employed in welding sections much below its capacity and when reduction of the upset force to a level suitable for the section being welded entails serious reduction of the upset speed. The speed of upsetting is of great importance and must not be allowed to fall below a minimum figure (Section E (c) (i)), and if the machine characteristics are such that satisfactory speed can only be attained by using an upset force greater than is appropriate to the section being welded, the best solution is to use a high speed with its accompanying large force and to obviate the effects of the latter by stopping the platen movement when sufficient upset is considered to have taken place. Under these conditions there is a possibility that the platen may rebound when it hits the stop. This must be avoided because steel at the high temperature prevailing near the weld has little ductility and any recoil may cause hot tearing of the metal.

E. WELDING VARIABLES

In order that a machine may be adjusted to suit the size of part and type of material being welded, consideration must be given to the factors of machine settings, etc., which may be varied in order to produce the desired result. It must be emphasised, however, that there are not generally any hard and fast rules; there is considerable flexibility and latitude in the combinations of factors which will give satisfactory results. Thus, after an approximate setting for satisfactory conditions has been reached it might be best to make final adjustment by way of the weld time and speed of platen travel, but a closely similar result could probably be attained by a change of transformer tappings.

(a) Open Circuit Secondary Voltage

For a given tapping the open circuit secondary voltage is the voltage measured between the dies with the transformer energised but with the work-pieces not in contact. The effect of this voltage on the quality of the weld is not yet fully understood, but it is generally held that the lowest voltage which will give a satisfactory flashing speed is advisable. As the voltage, and consequently the instantaneous current, is increased, the size of flash particles increases, leaving larger craters in the flashing faces to be closed by upset.

(b) Flashing

(i) *Current.*—During flashing the circuit is completed by a number of small localised contacts which are, in effect, the major resistance of the circuit, and result in the heat being generated almost entirely at the contacting points. The current during flashing is not controllable except by alteration of the secondary voltage or the speed of travel which determines how much contact area there is at any one time.

(ii) *Speed.*—The speed of travel of the movable platen during flashing must be of such that a continuous vigorous flashing action is maintained. If the speed is too high the area of contact between the abutting faces may become too large for flashing to continue. On the other hand, too low a speed of travel will result in contact being lost at times, so that flashing becomes intermittent and insufficient heat is generated.

As flashing continues and the temperature of the work-piece increases the rate of travel of the platen to maintain flashing can be increased and it is of advantage to do so. On automatic flash welding machines the device controlling platen travel is generally designed to give continuous acceleration of the platen during flashing.

(iii) *Temperature Gradient along the Work-pieces.*—During the flashing action the heat generated is concentrated at the abutting surfaces. Some of this heat is lost by radiation and by conduction through the work-piece to the dies, so setting up a temperature gradient.

The object is to arrange the temperature gradient so that there will be a plastic zone of adequate depth behind each flashing face to give satisfactory welding, but at the same time the zone should not be so deep that the upsetting movement and pressure will be largely absorbed in deforming this region instead of in expelling the overheated material and consolidating the weld.

The dies consist of a large mass of cold metal which draws off the heat from the work-piece. Therefore, too short an overhang of the work-pieces from the dies will set up an excessively steep temperature gradient with a plastic zone of inadequate depth. Increasing the amount of overhang will make the gradient flatter, but if carried too far may result in a distorted weld of poor quality.

If the two parts of the work-piece have similar geometrical and physical characteristics each piece should overhang the same distance from the dies, but if the heat capacities

of the two pieces differ or if they are of different materials, one of which requires a different temperature distribution from the other, then some benefit may be derived from making the overhangs unequal.

(iv) *Temperature of the Weld Face.*—The actual temperature of the weld face is also of paramount importance. If too cold there will be little extrusion at the lips of the weld, also there may be other indications from the behaviour of the machine that the upset pressure has been excessive due to cold material. If the weld is too hot the extrusion will be excessive and irregular and show burnt and pitted areas, while in extreme cases the ends may be melted and only partially in contact if limited upset is used.

(c) Upset

(i) *Speed.*—After the flashing action has raised the abutting surfaces to a suitable temperature, the movement of the platen is accelerated, forging the two parts together. This is a most important part of the flash welding process. In order to expel all slag and impurities, and to close up all flash craters, the faster the upset the better. The speed of upset attained is a function of the force applied to the platen, and of the resistance offered to it by the parts being welded. It is usually possible to determine whether upset speed has been sufficient by visual examination of the fin. If the weld region has a rounded appearance, the speed has been insufficient, and in all probability there will be considerable entrapped oxide, and the weld will be of low strength. Protruding lips on either side of the weld should be visible, showing that the hot material has been rapidly expelled. During the upsetting stroke the work-piece should be accelerated to a speed of at least $1\frac{1}{2}$ in. per second, but preferably, much higher.

FLASH WELDS SHOWING GOOD AND BAD JOINTS

Fig. 21. Excessive plastic zone behind welding faces, causing distortion and the likelihood of oxide entrapment due to insufficient weld interface pressure.

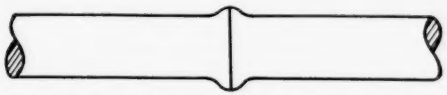


Fig. 22. Speed of upset insufficient to expel oxides and overheated metal.

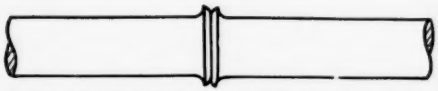


Fig. 23. Extruded lips at joint, characteristic of good weld.

(ii) *Pressure.*—The pressure that should be used during the upset depends to a large extent on the geometry of the work-piece; the higher the pressure which can be used without causing serious distortion or an undesirable large upset, the more effectively will the weld be consolidated and forged. As a rough guide, up to 4 tons per square inch may be used for mild steel, rising to about 8 tons per square inch for special alloy steels. If pre-heating is employed these pressures should be somewhat lower.

In the case of cam-operated machines the pressure is not directly under the control of the operator but must be allowed for in the machine design.

Care must be taken that the pressure is not so low that the speed of upsetting falls appreciably below the value specified in Section E (c) (i). Upset and Speed.

(iii) *Current Cut Off in Relation to Commencement of Upset.*—The point during the weld cycle at which current is cut off is important; if current ceases before upset starts, oxide forms immediately on the faces of the parts, while at the same time the temperature of the metal begins to fall. There is thus a considerable risk that sufficient material will not be expelled during the upset and that oxides will be trapped in the weld.

On the other hand, if the current is kept on too long after the commencement of upset there is a possibility, depending on the machine characteristics and the settings selected, of overheating at the weld; in particularly gross cases this has been known to result in the welded component being burnt into two parts.

Current may continue to flow so long as no over-heating occurs and should certainly continue for a few cycles after upset has commenced, say 5 cycles, *i.e.* one-tenth second. The exact number of cycles for a given component will depend on the type of work and can best be found by experiment.

Obviously, in view of the fact that only a few cycles of current are involved, some precise means of adjusting the cut-out point is necessary.

The use of a suitable recording ammeter in the primary circuit is helpful, not only when making the initial adjustment of the cut-off setting, but also as a check on the regular performance of the machine (see Figs. 24, 25, 26).

(d) Flashing and Upset Allowance

It is an essential feature of flash welding that a certain length from the end of each work-piece shall be burned away to generate the heat required for bringing the pieces to welding heat. Further, a certain amount of the length which remains at the end of the flashing stage is lost in the subsequent upsetting. With low carbon steels in the form of tube or sheet about two-thirds of the total material lost is burnt off in flashing, the remaining third being extruded during the upset period.

An approximate idea of allowances when welding equal sections can be obtained from Tables I and II and Figs. 27 and 28.

In certain cases a small gap may be required between the contacting faces, but generally it is sufficient for the work-pieces to rest lightly in contact. The initial overhang or projection from the dies must include the allowances as well as an adequate length to ensure a satisfactory temperature gradient.

When parts are required with small tolerances of length after welding, the allowances must be carefully controlled. In these circumstances, as pointed out in Section D (d), limited upset must be used and the allowances must be so adjusted and maintained that with the predetermined amount of upset, satisfactory conditions for welding are attained.

TYPICAL CHARTS FROM RECORDING AMMETER

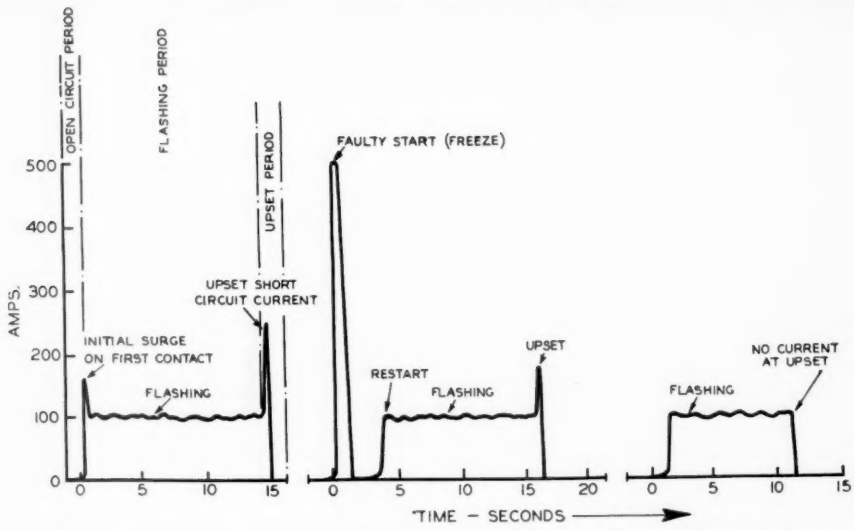


Fig. 24. Correct chart showing slight surge at start and considerable upset current.

Fig. 25. A bad start (freeze), but otherwise correct.

Fig. 26. No initial surge, but incorrect due to premature cut-off of current.

(e) Pre-heating

When sections thicker than about a $\frac{1}{2}$ in. are being welded the current required to initiate flashing directly from cold may be excessive, and in such circumstances it is advantageous or even necessary to prepare the work for continuous flashing by pre-heating.

The method is to bring the parts into moderately firm contact, sufficient to give a fairly large contact area and to pass current through the work-piece, heating the contact area by reason of its resistance. The flow of current is interrupted at intervals by drawing the faces apart so as to allow the heat to spread more uniformly over the faces and along the overhang. When the temperature of the work-piece is high enough to maintain continuous flashing the welding cycle is commenced.

Pre-heating may be made automatic, the pieces being repeatedly brought into contact and separated a number of times before flashing starts.

Pre-heating minimises the amount of metal required to be burnt off during flashing to achieve a satisfactory temperature distribution, and is therefore used on occasions to economise in expensive materials.

(f) Post-heating

When a flash weld is completed and the current cut off, the weld region is cooled very rapidly by conduction along the work-piece to the relatively massive dies or clamps and, in high carbon and certain alloy steels, this may result in excessive hardness of the weld region, which must be reduced by reheating this zone to a suitable tempering temperature. This reheating of the weld zone to achieve satisfactory uniformity of hardness is generally known as post-heating.

If a high rate of production from the welding machine is not required the post-heating operation may conveniently be performed in the machine, passing current through the welded component to raise its temperature to the required level. Before commencing the post-heating the welded component should be allowed to cool to a low temperature and during this cooling the clamps must be released to avoid the imposition of heavy stresses as a result of contraction.

If post-heating in the welding machine would delay production the heating may be carried out in furnaces or by any other convenient means.

F. TESTING AND INSPECTION

Inspection and testing are necessary to afford a check on the quality of welds being produced.

The particular types of defects most liable to occur in flash welds are:—

1. Inclusion of overheated and damaged material as a result of insufficient upset speed.
2. Entrapment of oxides as a result of cutting-off of the current too early.
3. Flaws of uncertain origin known as "flat spots" which appear to be discontinuities.

Mention has been made that visual inspection of the upset region affords a useful indication of whether welding conditions have been correct, but this is not, in itself, a sufficient indication of the quality of the weld.

Attempts have been made to test flash welds by non-destructive methods, including radiographic, magnetic, electrical and supersonic methods, but none of these has yet proved sufficiently sensitive and reliable for the purpose, and at present reliance must be placed on destructive methods of test.

Reference has already been made to the reproducibility of flash welds and in ordinary circumstances destructive testing of a very small proportion of the welds made can be taken as adequate guarantee of the general quality.

In a long run of repetition welding it is desirable not only to make a test after the welding variables have been adjusted, but also to make check tests periodically during the run, to ensure that the welding conditions have not altered. Further tests should be made when a new batch of material is involved or when any adjustment is made in the machine settings.

The tensile test will serve to show up rather gross defects which cause either a serious drop in U.T.S. or in ductility, but the test is not sufficiently discriminating above a moderately good standard of welding; it will not distinguish between fairly good and very good welds.

The Izod test is not easily applicable to flash welds owing to the difficulty of locating the plane of the weld precisely in a machined test piece. In almost all cases an Izod test will show a lower energy absorption when the notch is located in the plane of the weld, but insufficient data is available to indicate what decrease in the impact value of the original material should be looked for in the weld region.

At the present time the most revealing test for quality of flash welds appears to be a bend test. When the test is to be performed on the full section of the weld, it is desirable that all excess metal at the weld region should be machined away, otherwise the bend will not take place at the weld itself but will be concentrated at regions on either side.

If the material is subject to thermal hardening, the test piece should be tempered or otherwise heat treated before being bent, so as to eliminate the hardness gradient on each side of the weld. One objection to a simple bend test, whether free or guided, is that half the weld is in compression and therefore unlikely to fail even if defective.

In the present state of knowledge the bend test should be regarded as the most stringent one suitable for inspection and acceptance purposes. However, it does not discriminate among welds above a certain level of quality and, during the development of a technique for a particular application, the welder may wish to have a test which will reveal variations of quality among welds all sufficiently good to pass the ordinary bend test. For this purpose a repeated alternating bend test has been found useful.

A test piece taken from the welded component and with excess metal at the weld removed, is held at one end in a vice and the other end is bent through a moderate angle (say, 30 deg.) in one direction, then back through the initial position to the same angle in the opposite direction, then back again and so on until failure occurs. The number of bends to cause fracture, when compared with the number required to fracture a similar piece of the original material, gives a more or less quantitative measure of the weld quality.

G. METALLURGICAL CONSIDERATIONS

Like all welding processes, flash welding has its metallurgical aspects which must be given due consideration if the possibilities of the process are to be exploited to the full and unsatisfactory results are to be avoided. So far as steels are concerned the process has more desirable features and fewer metallurgical disadvantages than any other commonly used method of welding, but the position has not yet been reached when all disadvantages have been eliminated and account must still be taken of them.

During the heating cycle prior to welding a temperature gradient is established along each work-piece, ranging from the melting point of the steel at the flashing faces down to cool conditions adjoining the clamps. For convenience of description and consideration, the work-pieces may be divided into a series of temperature zones, though it must be appreciated that these zones are not clear cut, but merge into one another:

1. Metal heated to the very high temperatures at which its properties are permanently damaged. (Normally above 1200 deg. C. but below the melting point.)
2. Metal heated to temperatures at which the structure is coarsened. (From about 850 to 1200 deg. C.)
3. Metal heated to temperatures in and slightly below the normal heat treatment range. (From 700 to about 850 deg C.)
4. Metal heated to temperatures at the top limit of the tempering range. (650 to 700 deg. C.)
5. Metal which is not structurally affected.

When the work-pieces are brought together under the upsetting pressure, all the grossly overheated and damaged material of zone 1 should be forced out as a fin round the junction and the weld should be made in the metal of zone 2 which has not suffered any irreparable damage. To attain this result the upsetting speed must be adequate.

Material heated to temperatures around the lower end of zone 1 and upper end of zone 2, may, at some cooling rates, develop a form of intergranular weakness. In practice this is rarely observed in flash welds except in cases where the upsetting speed has been inadequate and an appreciable proportion of zone 1 remains in the completed weld instead of being squeezed out.

When the weld is completed a considerable region on each side of the junction is at temperatures within or above the heat treatment range and, when the current is cut off, these regions are cooled rapidly by conduction to the cooler regions of the work-piece. The rate of cooling is appreciably faster than air cooling and seems generally to be approximately similar to oil quenching of sections about 1 in. thick.

The effect of this cooling on the microstructure and mechanical properties depends on the class of steel being welded. In the case of mild steel and the low carbon low alloy steels which are not responsive to moderate cooling rates, the structure, apart from some coarsening near the junction, does not differ much from that of the normalised condition in which these steels are generally used, and the mechanical properties in the weld region are sufficiently similar to those of the original material to be acceptable without any further treatment.

High carbon steel and medium alloy steels which respond to moderate quenching rates are hardened to some extent for a distance on either side of the weld; this region is lacking in ductility in proportion to the hardening effect and it is not advisable to put the material into service in this condition.

The most desirable method of dealing with this heterogeneity of microstructure and properties would be to submit the whole welded component to a full heat treatment to develop the desired mechanical properties uniformly throughout, but this is not always possible and many components have to be welded in material which has already been heat treated to the required properties and which cannot be given more than a simple reheating treatment after welding. In such cases very good mechanical properties can be developed in the weld region by allowing it to cool down until the full hardening effect is obtained, and then reheating the hardened zone to a suitable tempering temperature to reduce the hardness to that of the original metal and to restore a large

measure of ductility. This tempering treatment can be carried out conveniently by resistance heating in the welding machine or by heating in furnaces or other suitable appliances. The time needed for tempering in the machine is only short, since the heat is being generated throughout the section and there is no need for the long soaking period to establish a uniform heat distribution through the section which is associated with furnace heating.

It has sometimes been suggested that the required hardness in the weld region can be attained directly by reducing the cooling rate, but this procedure is likely to give unsatisfactory results. It is true that in all hardenable steels hardness levels less than those corresponding to full quenching can be attained by an adjustment of the cooling rate, but in the alloy steels this generally leads to the formation of structures which, while of the required tensile strength, are seriously deficient in toughness and ductility.

For components which can only be given a simple tempering treatment after welding, there is a limit to the hardness of the steel which can be usefully welded without loss of strength near the joint. Next to the hardenable zone comes one in which the steel is fully tempered during the welding operation and the hardness of this zone is unaffected by any subsequent tempering treatment. Thus, if an attempt is made to weld a steel which has only been lightly tempered, there will be, after welding, a zone of variable width which is much softer than both the original material and the weld zone and which cannot be restored to its original hardness except by rehardening and tempering. Steels which are to be fully heat treated before welding and which can only be tempered after welding must be used in a condition closely approaching fully tempered.

In the case of cold worked steels the effects of the cold working are eliminated over the whole of the heated region, which is left appreciably weaker than the original material. The only exceptions to this limitation are those moderately alloyed steels which, in light sections, will undergo thermal hardening in the weld region to an extent which imparts to it a hardness approximating that of the original work hardened material. Even then there will be a narrow zone on each side of the weld and at some distance from it which has been softened but which was not raised to a sufficiently high temperature to undergo thermal hardening, but if these zones are narrow enough they will have little influence on the effective strength of the whole component.

A point of importance in regard to the quality of steel suitable for flash welding is that it should not contain excessive amounts of non-metallic inclusions. The upsetting action and the distortion of the fibre of the material in the immediate vicinity of the weld make it probable that large non-metallic inclusions which are not plastic at the welding temperature will result in internal fissures, while plastic ones may be forged into forms detrimental to the strength of the weld. It is this consideration which makes the high-sulphur free-machining steels, with their large content of manganese sulphide inclusions unsuitable for flash welding where the strength of the weld is important.

H. RECOMMENDED WELDING PROCEDURE

1. Examine stock for cleanliness and good fit in the dies.
2. Select approximate transformer tapping, speed control, flashing time and cut off.
3. Set up pieces with approximate overhang and check for alignment.
4. Adjust back stops if necessary.
5. Preheat if necessary.
6. Start flashing action and maintain for suitable time (alter speed if necessary to maintain good flashing).
7. Upset weld and cut off current.
8. Examine weld for appearance:
   If too cold, raise transformer tap, adjust flashing speed, or time, or increase overhang.
   If too hot, reduce transformer tap, adjust flashing speed, or time, or reduce overhang.
   If the weld appears right, try the effect of a lower transformer tap to see whether a good weld can still be produced.
9. When conditions for an apparently good weld are established, check the quality by some form of mechanical test.

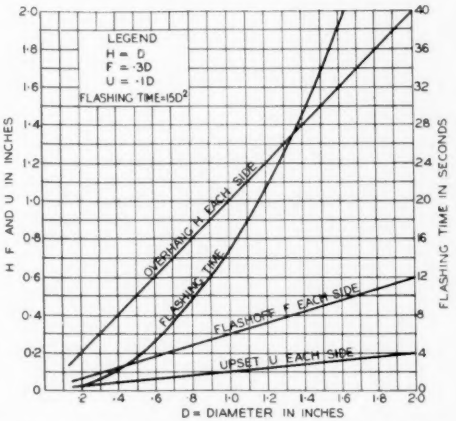


Fig. 27. Graph indicating allowances for flash welding without pre-heating mild steel round bars of equal diameter.

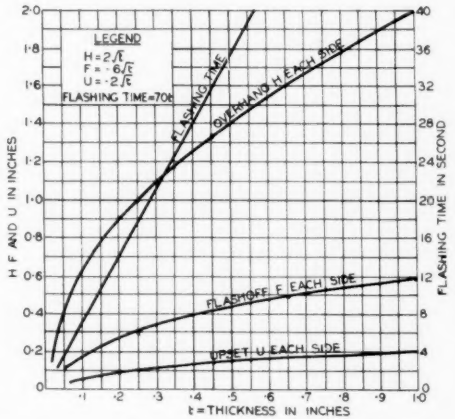


Fig. 28. Graph indicating allowance for flash welding without pre-heating mild steel flat strip or tube of equal thickness,

Table I.—Material Allowances for Flash Welding without Pre-Heating Mild Steel Round Bars of Equal Diameter

Diameter (inches)	Overhang Each Side (inches)	Flash Off Each Side (inches)	Upset Each Side (inches)	Flashing Time (seconds)
† D	H = D	F = 0·3D	U = 0·1D	F.T. = 15D²
0·2	0·2	0·06	0·02	0·5
0·4	0·4	0·12	0·04	2·5
0·6	0·6	0·18	0·06	5·5
0·8	0·8	0·24	0·08	9·5
1·0	1·0	0·30	0·10	15·0
1·2	1·2	0·36	0·12	22·0
1·4	1·4	0·42	0·14	29·0
1·6	1·6	0·48	0·16	38·0*
1·8	1·8	0·54	0·18	49·0*
2·0	2·0	0·60	0·20	60·0*

Table II.—Material Allowances for Flash Welding without Pre-Heating Mild Steel Flat Strip or Tube of Equal Thickness

Thickness (inches)	Overhang Each Side (inches)	Flash Off Each Side (inches)	Upset Each Side (inches)	Flashing Time (seconds)
† t	$H = 2\sqrt{t}$	$F = 0{\cdot}6\sqrt{t}$	$U = 0{\cdot}2\sqrt{t}$	F.T. = 70t
0·05	0·45	0·14	0·05	3·5
0·1	0·63	0·19	0·06	7·0
0·2	0·89	0·27	0·09	14·0
0·3	1·10	0·33	0·10	21·0
0·4	1·26	0·38	0·13	28·0
0·5	1·41	0·43	0·14	35·0
0·6	1·55	0·47	0·16	42·0*
0·7	1·67	0·50	0·17	49·0*
0·8	1·79	0·54	0·18	56·0*
0·9	1·90	0·57	0·19	63·0*
1·0	2·00	0·60	0·20	70·0*

* Probably better to pre-heat and so reduce flashing time and save material.

† Graphical representations of the above formulae are given in Figs. 27 and 28.

APPENDIX

(a) Power Supplies

The question of power supply is important for flash welding machines, and the following information may be taken as a general guide to their connection to the electricity mains.

The transformer in the machine is normally single phase arranged for connection across two phases of the L.T. electricity supply, the latter being now almost standardised throughout the country at 415 volts, 50 cycles, 3 phase.

The connection of single phase flash welding machines to mains supplies need not cause any problems of out-of-balance load provided care is taken not to overload the supply lines and the electricity authorities are consulted beforehand. The following information may be taken as a general approach to the problem in the order of preference.

(i) *Normal Single Phase Supply*

Providing there is a reasonable margin of kVA. capacity in the sub-station transformer feeding the L.T. supply to the factory, no objection is normally made by the supply authorities.

Although it is usual to put forward the kVA rating of the flash welding machine to the supply authorities, it is preferable to supply a loading graph representative of the load taken when the machine is operating to the maximum capacity, together with a duty cycle of the flash welding machine, so that the supply authorities may appreciate the likely demand on a current and time basis.

The provision of such a loading graph will show that in the case of straight flash welding machines the demand made during the flashing period is fairly steady, while at the termination of the weld there is a momentary peak, the intensity of which is normally about three times the current demand of the flashing period.

As the momentary peak demand is only of a few cycles duration, it does not present any real problem, provided that the supply cables are of adequate size to prevent a momentary voltage drop sufficient to cause the lights in the vicinity to flicker.

For flash welding machines arranged for pre-heating application, the conditions are somewhat different, in that, during the pre-heating cycle a current demand of maximum intensity is made at each reciprocation extending over a period of seconds, followed by a short flashing period of approximately one-third the pre-heating demand, and ultimately a momentary peak demand similar to that for a straight flash weld. It is obvious, therefore, that for pre-heating more careful consideration must be given to the question of power supply.

As the kVA rating of flash welding machine transformers is usually assessed on a single-phase intermittent basis, and the sub-station transformer on a three-phase continuous basis, special consideration must be given to the size of the sub-station transformer taking into account the load diversity.

(ii) *Three to One Phase Supply*

At one time it was considered advisable in some instances to arrange the transformer in the welding machine to be three to one phase, or alternatively, to provide an external three to one phase transformer, so that connection could be made to all three phases of an L.T. supply. On consideration of the fact that the loading conditions were only split up in the ratio of 1/2/1 on the three phases with a varying power factor from one phase to another, this practice has now almost been discontinued in favour of direct single phase connection.

In some instances, however, it has been advisable to fit a three to one phase sub-station transformer in the sub-station, that is, with H.T. three-phase input and L.T. single-phase output. This type of transformer is more expensive than the standard step down transformer, and the advantages obtained seldom justify the additional expenditure.

(iii) *Three Phase Connection*

A motor driven alternator, giving a single-phase supply to the welding machine will give perfect balance on all phases.

A second method involves the use of reactors and condensers, suitably connected between the two phases to which the flash welding machine is connected and the remaining phase. This arrangement gives a phase balance of the order of 1 1·9/1·7 at a given loading condition.

More recently, developments have been made using a special three winding transformer in the welding machine, which is controlled by ignitron tubes and gives balanced three-phase loading.

In all these methods the initial capital expenditure must be considered as it is likely to be high and, as already stated, providing an adequate supply is available with a margin of capacity in the sub-station transformer, no three-phase arrangement is normally called for, nor is it justified.

(b) Power Factor Correction

An important aspect in supply conditions is, however, the question of power factor correction. All flash welding machine transformers have an inherently low power factor which, on the average, can be assumed at 0·45 lagging.

This low power factor can be improved by the introduction of static condensers of suitable capacitance, which will improve the power factor from 0·45 to 0·85 or even 0·9, although 0·85 is generally acceptable by the supply authorities.

The advantage of power factor correction is twofold, in that, not only is the power factor corrected, but the maximum current demand is also reduced.

It is important that the power factor correction condenser when installed in conjunction with the flash welding machine, should be connected in such a manner that it is brought in by the contactor switch controlling the primary circuit of the welding machine transformer, thereby applying correction only during the welding time, otherwise it might, in some instances, provide a leading power factor when the machine is not in use.

The recommended size of the power factor correction condenser depends on the capacity of the welding machine transformer and may be had on request to the manufacturers of the machine.

(c) Summary

Taking into consideration the alternatives set out above, it will be noted that the question of power supply is one which should be discussed with the power supply authorities for each particular installation, as so much depends on loading conditions at the site where the welding machine is being installed. Summarising generally, the first approach should always be made for direct single phase connection to two phases of the three phase mains, fed by sub-station transformers of reasonable capacity, and only when difficulties are met in this approach should any of the other alternatives be considered. Due thought should be given to improvement of power factor, since this also reduces the maximum current demand.

R.67

The Effect of Strain-Hardening on the Equalisation of Moments in the Simple Plastic Theory

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1. INTRODUCTION

The simple plastic theory, and its application to encastré beams and rectangular portal frames, has been adequately described elsewhere.[1] According to this theory, a readjustment of bending moments tends to take place after yield has occurred, until at collapse, full plastic moment is developed at a number of sections. When considering members of uniform cross section, this means that at collapse, the bending moments at these sections are equal, and hence this process has been called the "principle of equalisation of moments." Thus the collapse load of a redundant beam or portal frame may be deduced from purely statical considerations, without in any way considering the equations of flexure of the members.

As long as the whole structure remains elastic, stress distributions across members are of the type shown in Fig. 1*a*, where the extreme fibre stress f is less than the upper yield stress f_c. Assuming the stress-strain curve shown by OABD′ in Fig. 2, the stress distribution after yield stress has been reached at a section will take the the form shown in Fig. 1*b*. There is then a tendency for the bending moments to equalise due to the greatly increased flexure which takes place at the sections with the greatest degree of plasticity. However, this process of equalisation of bending moments may not be complete even when a state of full plasticity (represented by Fig. 1*c*) has been reached at some section. Under these circumstances, it is assumed that a "plastic hinge" forms at such sections, since the stress distribution of Fig. 1*c* corresponds to infinite curvature. Ultimately, sufficient "plastic hinges" are formed for the structure to become a simple mechanism, and collapse occurs.

The assumption of "plastic hinges" is only an approximation, and is really prevented by the presence of strain-hardening. Thus a closer approximation to the stress strain curve for mild steel would be given by OABCD in Fig. 2. If the strain corresponding to point C is ε_s and that at yield is ε_y, then the limit of application of the simple plastic theory is attained with the stress distribution shown in Fig. 1*d*. If the total depth of the section is $2d$, the depth of the elastic core at this limit of the simple theory is $2\varepsilon_y/\varepsilon_s d$. Thereafter the extreme fibre stresses increase with increase of strain, the increase of stress being E_s times the increase of strain where E_s is the slope of the line CD in Fig. 2. Hence stress distributions of the type shown in Fig. 1*e* will be obtained, and the bending moment may increase beyond the "full plastic moment" given by the stress distribution in Fig. 1*c*.

The approximations made in the simple plastic theory make it desirable to check how far equalisation of moments can occur when allowance is made for strain-hardening. Tests have indicated that for mild steel beams and portal frames, the principle of equalisation of moments gives a close estimate of the bending moment distribution at collapse, but no tests have hitherto been made on higher carbon steels. However, tests have been performed on simply supported beams of varying carbon content[2], and it has been shown that stress-strain curves of the type given by OABCD in Fig. 2 are capable of providing a satisfactory explanation of their behaviour. In the present report, two of these stress-strain curves have been used for a theoretical investigation of two rectangular beam problems. A comparison is made between the plastic theory which ignores strain-hardening and that which takes strain-hardening into account. For the purposes of comparison, the same problems are also solved for an I-beam by using Hrennikoff's[3] deflection coefficients for mild steel beams bent beyond the elastic limit.

2. STRESS-STRAIN CURVES

The stress-strain curve assumed by Hrennikoff in calculating his deflection coefficients is shown in Fig. 3*a*. Hrennikoff neglected upper yield stress entirely. The strain-hardening line CD is curved, but in the range used in this report, has an approximately uniform

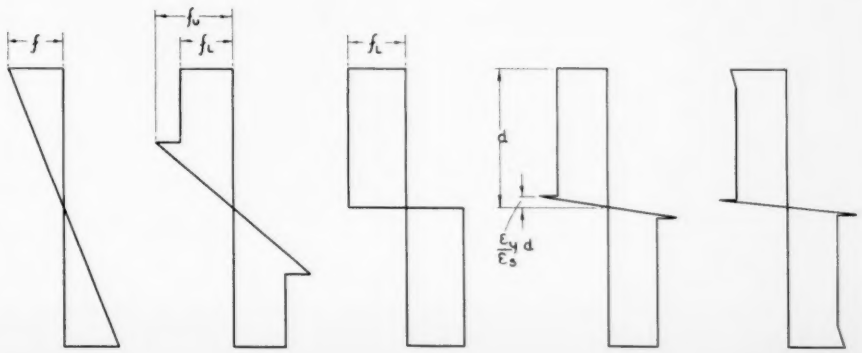

Fig. 1.

slope of 250 tons per sq. in. The main mechanical properties of the steel satisfy the requirements of the 1940 Specifications of the American Railway Engineering Association for fixed-span railway bridges.

The two steels selected for study from Roderick and Heyman's report[2] (steels A and D) had the stress-strain curves shown in Fig. 3*b* and 3*c*. The percentage compositions are given in Table I.

The main constants of the stress-strain curves for the three steels are given in Table II.

Table I

Steel	Composition (per cent.)						
	C	Si	Mn	S	P	Ni	Cr
A	0·28	0·20	0·64	0·030	0·029	0·080	0·09
D	0·89	0·26	0·26	0·037	0·032	0·070	0·01

Table II

Steel	Lower Yield Stress Tons per sq. in.	$\beta = \frac{f_u}{f_l}$	Modulus of Elasticity Tons per sq. in.	$S = \frac{E}{E_s}$	$r = \frac{\varepsilon_s}{\varepsilon_y}$
Hrennikoff	14·7	1·00	13,400	54·0	16·4
A	22·0	1·33	13,400	26·9	9·2
D	34·0	1·04	13,400	10·2	1·5

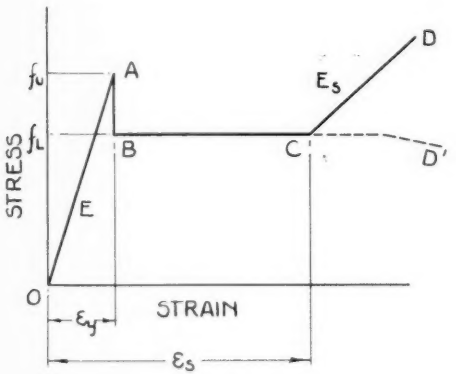

Fig. 2.

3. SINGLE CONCENTRATED LOAD

A partially encastré beam AB (Fig. 4*a*) carries a central concentrated load. The relationship between end moment and end rotation is assumed linear at all stages of loading and is such that while the beam is elastic, the central moment is twice the end moment. The results for Hrennikoff's steel and steels A and D are represented graphically in Figs. 5, 6 and 7 respectively.

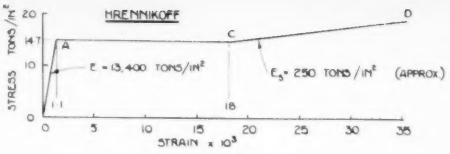

Fig. 3a.

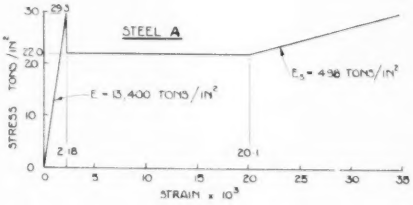

Fig. 3b.

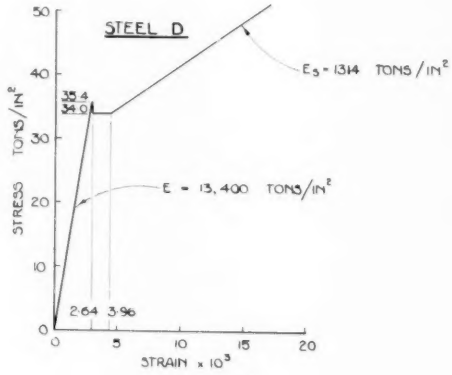

Fig. 3c.

The load-deflection curve for Hrennikoff's steel is given in Fig. 5*a*. The I-beam is assumed to have flanges whose combined area is equal to the area of the web. The deflection (plotted horizontally) is given in terms of the deflection when yield first occurs, and the load is expressed as a ratio of that load which would produce collapse according to the simple plastic theory. The full line gives the load-deflection curve when strain-hardening is allowed for, while the dotted line shows the load deflection curve according to the simple plastic theory where this deviates from the former. Yield first occurs in the extreme fibres under the load at A. According to the simple plastic theory, full plastic moment is reached at the centre at the load corresponding to point B, and a plastic hinge then forms at this section. Yield occurs at the ends at C, and full plastic moment is reached at the ends

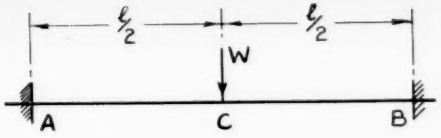

Fig. 4a.

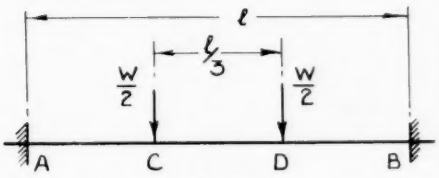

Fig. 4b.

at D, after which the deflection increases indefinitely without any further increase of load. When strain-hardening is allowed for, it first occurs at the centre at a load corresponding to E. Yield at the end occurs at F, and strain-hardening occurs at the ends at G. As would be expected, the deflections when strain-hardening is allowed for are less than when it is ignored.

The relationship between end and central bending moments and load is shown in Fig. 5*b*. The bending moments (plotted vertically) are given in terms of the full plastic moment according to the plastic theory ignoring strain-hardening. Despite the presence of strain-hardening, the bending moments tend to equalise after yield has occurred. When the load is equal to the collapse load according to the simple theory, the ratios of central and end bending moments to the full plastic moment are as given in line one of Table III. The error involved in assuming that the bending moment distribution is given by the simple plastic theory is thus only about 5 per cent. The variation of extreme fibre stress at the end and central sections with load is shown in Fig. 5*c*.

Table III

Load Distribution	Steel	Section	Central Moment ÷ Full Plastic Moment	End Moment ÷ Full Plastic Moment	Deflection ÷ Deflection at Yield
Central Concentrated Load	Hrennikoff	I	1·051	0·949	2·764
	A	Rect	1·072	0·928	2·651
	D	Rect	1·200	0·800	2·629
Two Equal Concentrated Loads	Hrennikoff	I	·991	1·009	2·831
	A	Rect	·991	1·009	2·782
	D	Rect	1·076	·924	3·024

The results for steel A, given in Figs. 6*a*, *b* and *c* and line two of Table III are similar in general character to those for the Hrennikoff steel. However, the results obtained for steel D (Figs. 7*a*, *b* and *c* and line three of Table III) are very different due to the much earlier attainment of strain-hardening. This goes a long way to prevent the equalisation of moments. At a load equal to the collapse load according to the simple plastic theory, the central and end bending moments are respectively 20 per cent. above and below the full plastic moments.

4. TWO-POINT LOADS

A partially encastré beam AB (Fig. 4*b*) carries two equal concentrated loads at its third points C and D. The ends have an equal degree of fixity such that in the elastic range the central bending moment is twice the end bending moment. It follows from the symmetry of the beam and the load distribution that the central length CD is subjected at all stages of loading to a uniform bending moment.

The load-deflection, load-bending moment and load-extreme fibre stress curves for the Hrennikoff steel are given in Figs. 8*a*, *b* and *c* respectively. Referring to Fig. 8*a*, yield stress is first reached in the extreme fibres at the centre at a load corresponding to point A. This leads to increased flexure along the whole of the central length of the beam, with the result that the end bending moments increase much more rapidly than the central bending moment. Yield stress is reached at the ends of the beam at C and, according to the simple plastic theory, full plasticity is developed at the ends at D. Thereafter the deflection increases very rapidly with load, and full plasticity is not developed over the central length of the beam until this deflection is infinite. When strain-hardening is taken into account, it is found that strain-hardening first occurs at the ends at G, and within the range of calculations made, is never reached over the central length. It will be seen from Fig. 8*b* that equalisation of bending moments takes place before strain-hardening occurs and before the load has reached the collapse value according to the simple plastic theory. At this latter load, the difference between the end and central bending moments and the full plastic moment is less than 1 per cent., as will be seen from line four of Table III.

The results for steel A (see Figs. 9*a*, *b* and *c* and line five of Table III) are very similar to those for the Hrennikoff steel. As for the single concentrated load, however, steel D gives results (see Figs. 10*a*, *b*, *c* and line six of Table III) which differ considerably from those for the other two steels. Referring to Fig. 10*a*, strain-hardening is reached at the centre (point E) before yield occurs at the ends (point F), and although equalisation of bending moments does ultimately take place (see Fig. 10*b*), it does so at a load 1·19 times the collapse load according to the simple plastic theory. At a load equal to this collapse load, the central bending moment is still 7·6 per cent. greater and the end bending moments are still 7·6 per cent. less than the full plastic moment.

5. CONCLUSIONS

The extent to which the equalisation of moments predicted by the simple plastic theory can take place depends upon the nature of the steel and the disposition of the loads. Equalisation of moments takes place more readily if yield first occurs in a region which at collapse is subjected to a uniform bending moment. In general, this condition will not be satisfied, and for the simple "plastic hinge" theory to give bending moments at collapse within 5-10 per cent. of the true values, there must be a pure plastic range in the stress-strain curve of about ten times the strain at yield. This requirement is satisfied by structural mild steel, but not by higher carbon and alloy steels.

The simple plastic theory is satisfactory as a basis for designing mild steel structures because it gives a reasonable estimate of the loads at which deflections start to increase rapidly, and of the bending moment distributions under such loads. It will be seen from Figs. 5*a*, 6*a*, 8*a* and 9*a* that for Hrennikoff's steel and steel A, deflections start to increase rapidly soon after the collapse load predicted by the simple plastic theory has been exceeded. For steel D, however (Figs. 7*a* and 10*a*), there is no definite point

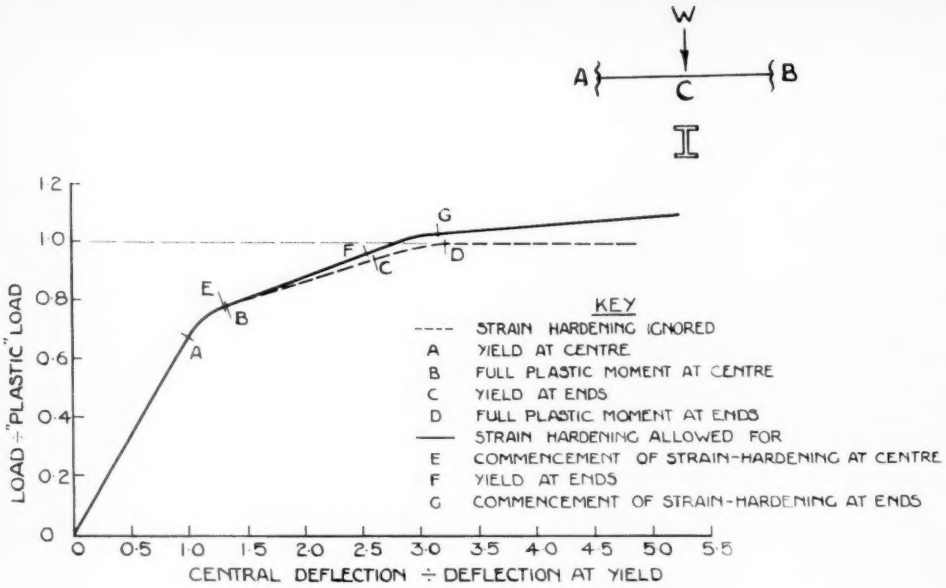

Fig. 5a. I-Beam. Mild steel. Central load. Load/deflection curve.

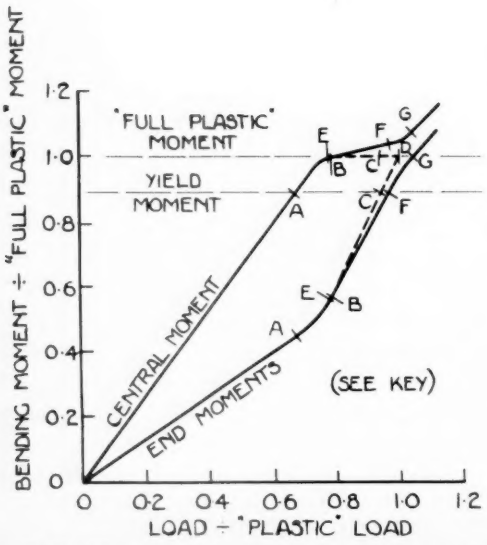

Fig. 5b. I-Beam. Mild steel. Central load. Load/bending moment curves.

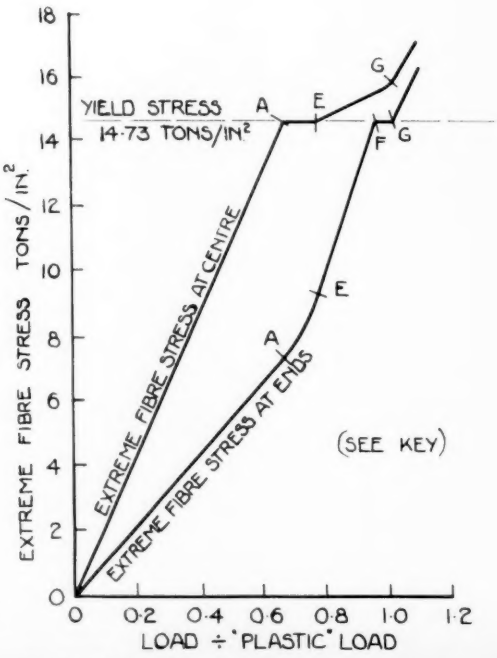

Fig. 5c. I-Beam. Mild steel. Central Load. Load/extreme fibre stress curves.

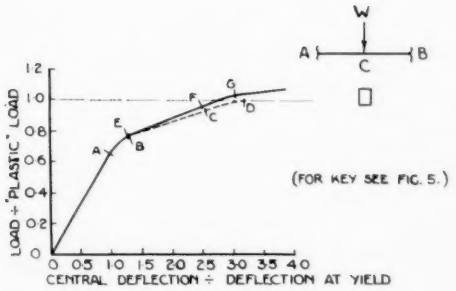

Fig. 6a. Rectangular beam, Steel A. Central load. Load/deflection curve.

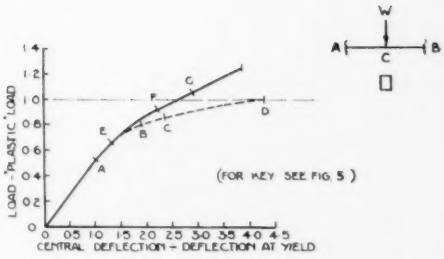

Fig. 7a. Rectangular beam, Steel D. Central load. Load/deflection curve.

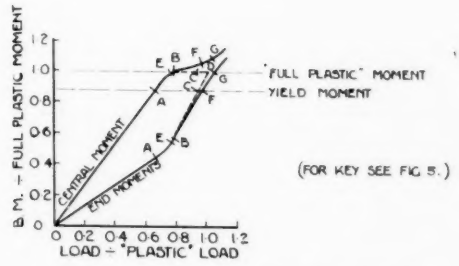

Fig. 6b. Rectangular beam, Steel A. Central load. Load/bending moment curves.

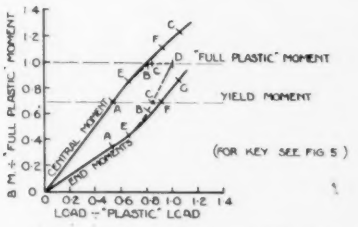

Fig. 7b. Rectangular beam, Steel D. Central load. Load/bending moment curves.

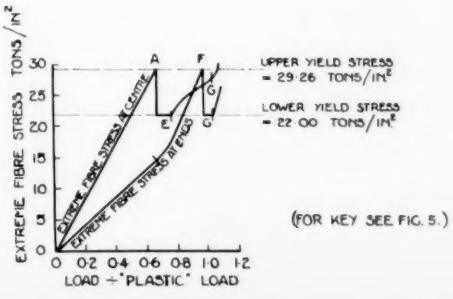
EXTREME FIBRE STRESS TONS/IN²
UPPER YIELD STRESS = 29·26 TONS/IN²
LOWER YIELD STRESS = 22·00 TONS/IN²
EXTREME FIBRE STRESS AT CENTRE
EXTREME FIBRE STRESS AT ENDS
(FOR KEY SEE FIG. 5.)
LOAD ÷ "PLASTIC" LOAD

Fig. 6c. Rectangular beam, Steel A. Central Load. Load/extreme fibre stress curves.

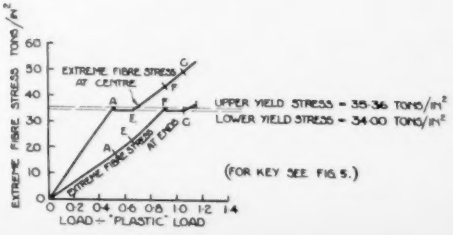
EXTREME FIBRE STRESS TONS/IN²
EXTREME FIBRE STRESS AT CENTRE
EXTREME FIBRE STRESS AT ENDS
UPPER YIELD STRESS = 35·36 TONS/IN²
LOWER YIELD STRESS = 34·00 TONS/IN²
(FOR KEY SEE FIG. 5.)
LOAD ÷ "PLASTIC" LOAD

Fig. 7c. Rectangular beam, Steel D. Central load. Load/extreme fibre stress curves.

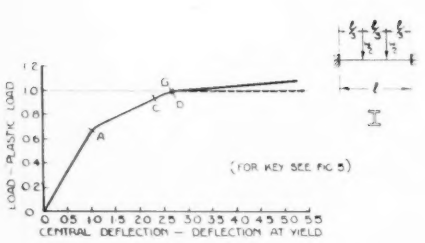

Fig. 8a. I-Beam, mild steel. Two-point load. Load/deflection curve

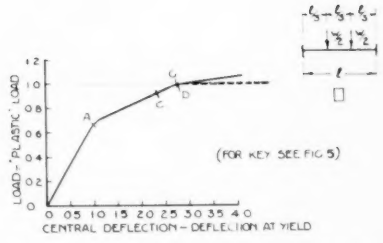

Fig. 9a. Rectangular beam, Steel A. Two-point load. Load/deflection curve.

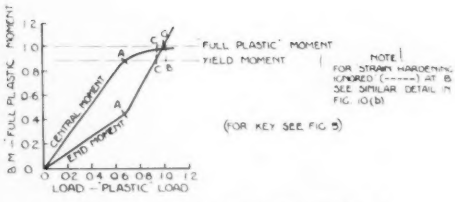

Fig. 8b. I-beam, mild steel. Two-point load. Load/bending moment curves

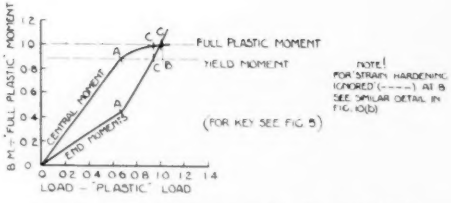

Fig. 9b. Rectangular beam, steel A. Two-point load. Load/bending moment curves.

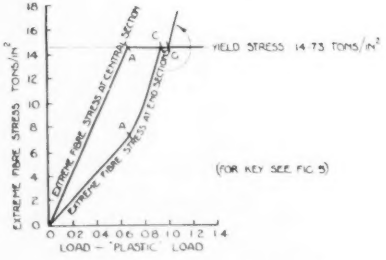
EXTREME FIBRE STRESS TONS/in²
LOAD – 'PLASTIC' LOAD
YIELD STRESS 14.73 TONS/in²
EXTREME FIBRE STRESS AT CENTRAL SECTION
EXTREME FIBRE STRESS AT END SECTION
(FOR KEY SEE FIG 5)

Fig. 8c. I-beam, mild steel. Two-point load. Load/extreme fibre stress curves.

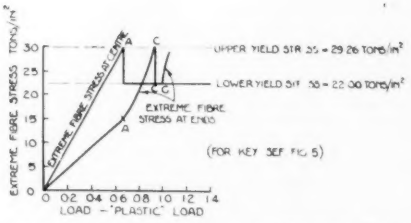
EXTREME FIBRE STRESS TONS/in²
LOAD – 'PLASTIC' LOAD
UPPER YIELD STR 25 = 29.26 TONS/in²
LOWER YIELD STR 18 = 22.00 TONS/in²
EXTREME FIBRE STRESS AT CENTRE
EXTREME FIBRE STRESS AT ENDS
(FOR KEY SEE FIG 5)

Fig. 9c. Rectangular beam, steel A. Two-point load. Load/extreme fibre stress curves.

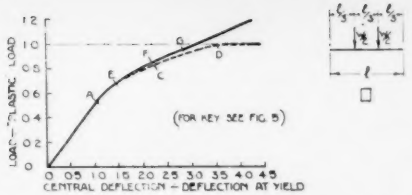

Fig. 10a. Rectangular beam, steel D. Two-point load. Load/deflection curves.

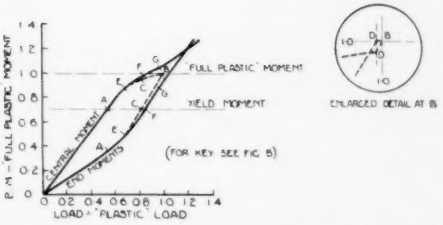

Fig. 10b. Rectangular beam, steel D. Two-point load. Load/bending moment curves.

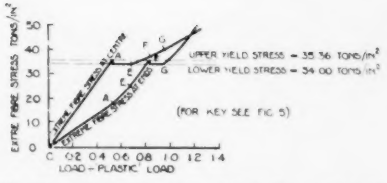
EXTRE FIBRE STRESS TONS/in²
LOAD ÷ 'PLASTIC' LOAD
UPPER YIELD STRESS = 35·36 TONS/in²
LOWER YIELD STRESS = 34·00 TONS/in²
(FOR KEY SEE FIG. 5)

Fig. 10c. Rectangular beam, steel D. Two-point load. Load/extreme fibre stress curves.

of collapse, and the load necessary to produce a given deflection increases appreciably as the deflection is increased. Hence, if an ultimate design method for steels with only a small plastic range is to be developed, considerable attention must be given to the precise maximum deflections which are to be allowed.

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